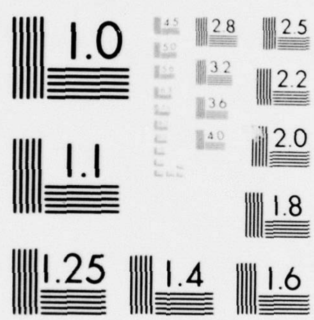
AD-A037 617 ARMY ENVIRONMENTAL HYGIENE AGENCY ABERDEEN PROVING GR--ETC F/G 6/18
OPTICAL HAZARDS OF WEATHER SERVICE INSTRUMENTATION, JANUARY 197--ETC(U)
JAN 77 D H SLINEY, W J MARSHALL
UNCLASSIFIED USAEHA-42-0321-77 NL

1 OF 1
ADA037617

END
DATE
FILMED
4-77


1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

(12)

NONIONIZING RADIATION PROTECTION SPECIAL STUDY NO. 42-0321-77
OPTICAL HAZARDS OF WEATHER SERVICE INSTRUMENTATION
JANUARY 1977

SERVING THE ARMY IN ITS PREVENTIVE MEDICINE PROGRAM

SENTINEL of HEALTH

Approved for public release; distribution unlimited.

US ARMY
ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MD 21010

DEPARTMENT OF THE ARMY
U. S. ARMY ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010

HSE-RL/WP

28 MAR 1977

NONIONIZING RADIATION PROTECTION SPECIAL STUDY NO. 42-0321-77
OPTICAL HAZARDS OF WEATHER SERVICE INSTRUMENTATION
JANUARY 1977

ABSTRACT

A nonionizing radiation protection special study of five types of weather instruments was performed by the US Army Environmental Hygiene Agency during January 1977. It was determined that the three ceilometers, one transmissometer and a laser weather identifier did not represent optical hazards under normal use for expected viewing conditions. However, during maintenance or testing, it was conceivable that optically aided viewing within the beams of these instruments could be hazardous. It is recommended that appropriate warning statements be placed in the instrument manuals and that the output characteristics of the laser weather identifier be limited to preclude most viewing hazards.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER USAEHA 42-0321-77	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) NONIONIZING RADIATION PROTECTION SPECIAL STUDY NO. 42-0321-77, OPTICAL HAZARDS OF WEATHER SERVICE INSTRUMENTATION, JANUARY 1977	5. TYPE OF REPORT & PERIOD COVERED Special Study January 1977
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David H. Sliney, Wesley J. Marshall, Pedro F. Del Valle	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS USA Environmental Hygiene Agency, Aberdeen Proving Ground, MD 21010	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Commander, USA Health Services Command, Fort Sam Houston, TX 78234	12. REPORT DATE 12 21 p.
	13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

Nonionizing Radiation Protection Special Study,

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

038 150

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Laser Meteorological Equ

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A nonionizing radiation protection special study of five types of weather instruments was performed by the US Army Environmental Hygiene Agency during January 1977. It was determined that the three ceilometers, one transmissometer and a laser weather identifier did not represent optical hazards under normal use for expected viewing conditions. However, during maintenance or testing, it was conceivable that optically aided viewing within the beams of these instruments could be hazardous.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

DEPARTMENT OF THE ARMY
U. S. ARMY ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010

HSE-RL/WP

NONIONIZING RADIATION PROTECTION SPECIAL STUDY NO. 42-0321-77
OPTICAL HAZARDS OF WEATHER SERVICE INSTRUMENTATION
JANUARY 1977

1. AUTHORITY. Letter, US Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Test and Evaluation Division, Sterling, Virginia, 7 December 1976, to the Surgeon General, Department of the Army, subject: Evaluation of Lasers of NWS/T&ED, and indorsements thereto.

2. REFERENCES. See Appendix A for listing of references.

3. PURPOSE. To evaluate the hazards to personnel operating and in the vicinity of lasers and other high intensity optical radiation sources used in weather instrumentation, and to make necessary recommendations to protect personnel from exposure to potentially hazardous optical radiation from this equipment.

4. GENERAL.

a. Background. The National Weather Service (NWS) is presently evaluating new meteorological instruments that use lasers and other high intensity optical radiation sources that are potentially hazardous. Earlier instruments with optical sources have been in use for some time at weather stations throughout the United States. Some of this equipment has been used by the US Army and the other armed services. The NWS requested the US Army Environmental Hygiene Agency (USAEHA) to evaluate this instrumentation (paragraph 1). Personnel from USAEHA performed radiometric measurements of representative equipment located at the NWS Test and Evaluation Division's facility at Sterling, Virginia (Dulles Airport), on 4 January 1977. Most of the devices evaluated were cloud-height ceilometers:

(1) Sperry LIDAR Model LC5000/1 Ceilometer, which used a gallium-arsenide (Ga-As) infrared-emitting laser diode.

(2) Impulsephysik Videograph, Model B, 147.122/222-G1, which used a xenon flashlamp.

(3) Crouse-Hinds Co. (or Carlisle and Finch Co.) Ceiling Light Projector, ML-121, which used a quartz-tungsten lamp.

® Videograph is a registered trade name of Impulsephysik, Hamburg, West Germany. Use of trademarked names does not imply endorsement by the US Army, but is used only to assist in identification of a specific product.

(4) Crouse-Hinds Rotating Beam Ceilometer Model K211, which used a quartz-tungsten lamp with a near-infrared-pass filter.

(5) NWS Laser Weather Identifier, which used a helium-neon (He-Ne) laser and a carbon-dioxide (CO_2) laser.

b. Instrumentation.

(1) EG&G Model 580 Radiometer System.

(2) Scientech Model 360 Disc Calorimeter.

(3) United Detector Technology Model 40X Optometer.

(4) Nikon F Camera with Kodak HIE-135 Infrared Film.

(5) Calibrated Circular Apertures.

(6) Corion Laser Line Filter (905 nm).

c. Abbreviations and Units. A table of commonly used radiometric units and their abbreviations is supplied as Appendix B.

5. FINDINGS.

a. Sperry LIDAR Model LC5000/1 Ceilometer.

(1) Description. Figure 1a shows the LC5000/1 Ceilometer, which was being evaluated by the NWS and was not yet in general use at weather stations. It measured cloud base height from 100 ft (30 m) to 5,000 ft (1,525 m). The infrared transmitter consisted of an array of Ga-As laser diodes which were fiber-optically coupled to produce a single source as shown in the infrared photograph (Figure 1b). The laser emission was collimated by a reflecting telescope and directed vertically upward. The collimated laser beam leaves the tubular shroud at a height of approximately 140 cm aboveground. Figure 1c shows the emergent beam irradiance pattern.

(2) Manufacturer's Specifications.

Output Peak Power: 350 W

Wavelength: 905 nm ± 10 nm

Source Aperture: 0.43 mm by 0.43 mm

Pulse Duration: 60-80 ns

Energy Output per Pulse: 2.4×10^{-5} J

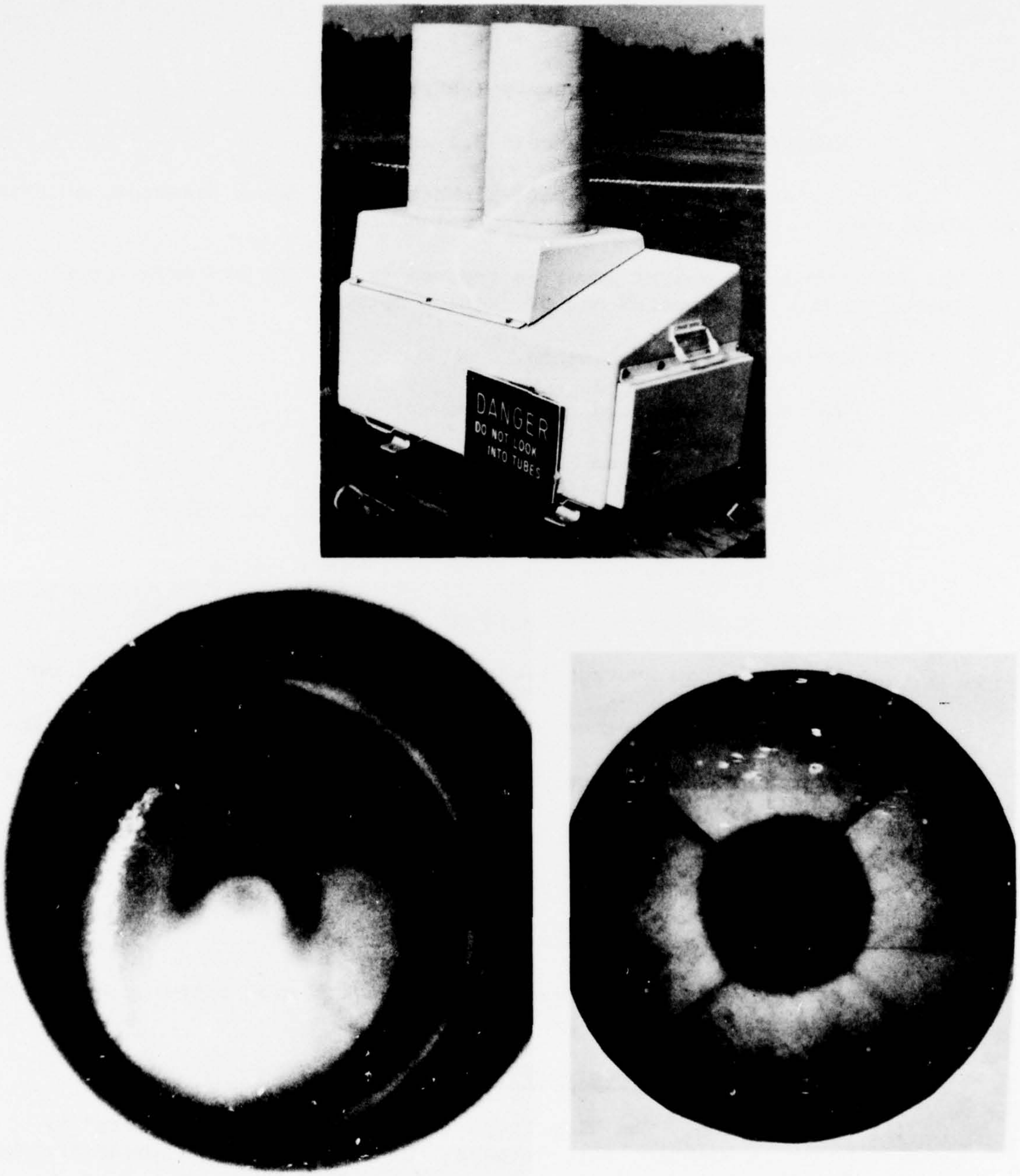


FIGURE 1. Sperry LIDAR Model LC5000/1 Ceilometer (top) and infrared photographs of the projected source (lower left) and irradiance pattern (lower right).

Average Power Output of Array: 0.12 W

Pulse Repetition Frequency (PRF): 5 kHz

Emergent Beam Divergence: 0.1 mrad

Collimating Optics: Dall-Kirkham F/2.0, 20-cm diameter, 40.6-cm focal length, catadioptic reflecting telescope

The aforementioned output power is assumed to be from the array prior to losses in the fiber optics and projection optics.

(3) Radiometric Measurements.

Estimated Projected Average Power: 8 mW

Wavelength: 905 nm

Emergent Beam Irradiance (7-mm aperture): 66 $\mu W/cm^2$

Beam Irradiance at 115 m (7-mm aperture): 50 $\mu W/cm^2$

Beam Irradiance at 240 m (7-mm aperture): 20 $\mu W/cm^2$

Emergent Beam Average Power through a 10-cm aperture: 2.1 mW

Emergent Beam Average Power through a 7.5-cm aperture: 1.6 mW

Emergent Beam Average Power through a 5.0-cm aperture: 0.79 mW

Emergent Beam Average Power through a 2.5-cm aperture: 0.11 mW

Emergent Beam Average Power through a 0.7-cm aperture: 0.026 mW

Effective Emergent Beam Diameter: 8 cm

Effective Emergent Beam Divergence: 0.3 mrad based upon best fit of data as shown in Figure 2.

b. Impulsephysik Videograph®, Model B.

(1) Description. The Videograph (Figure 3a) was manufactured by Impulsephysik in Hamburg, West Germany. It was used to determine atmospheric

---

® Videograph is a registered trade name of Impulsephysik, Hamburg, West Germany. Use of trademarked names does not imply endorsement by the US Army, but is used only to assist in identification of a specific product.

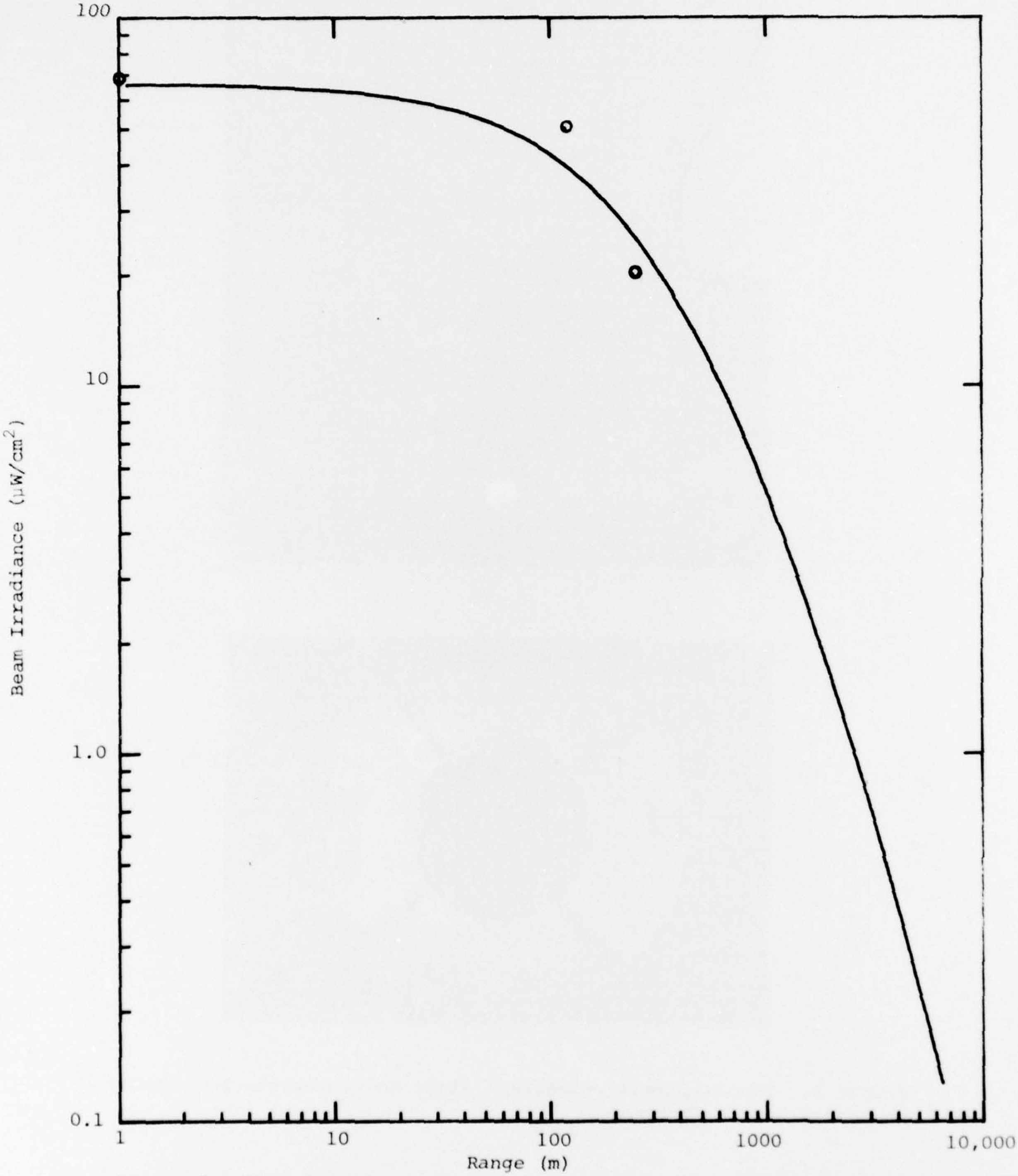


Figure 2. Beam Irradiance for Sperry LIDAR Model LC5000/1 Ceilometer. Circles are Measured Points which Indicate Beam was Slightly Focused at Approximately 100 m on the Device Measured.

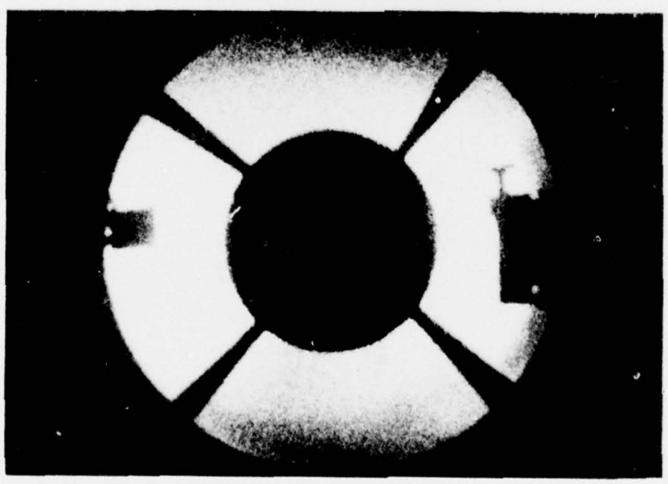


FIGURE 3. Impulsephysik Videograph (top) and intrabeam photograph of projected source (bottom).

visibility by means of measuring the atmospheric backscatter. It used a 2-kV, 200-W-s xenon model GE FT-230 flashlamp which emitted 50-μs pulses at 3.0 ± 0.3 Hz. The beam is directed slightly upward and leaves the instrument at a height of 140 cm to 170 cm.

(2) Radiometric Measurements. Figure 3b shows the projected source distribution. The characteristic spectra of a 2,000-V xenon-arc flash is given in Figure 4. The output characteristics measured were:

Emergent Beam Aperture Diameter: 15 cm

Emergent Beam Irradiance (for 20° f.o.v.): 0.7 $\mu J/cm^2$ per pulse

Illuminance: 6 lx•s

Irradiance to 70 cm: 0.58 $\mu J/cm^2$ per pulse

Illuminance at 400 cm: 3.5 lx•s

Luminous Efficacy of Radiation: 110 lm/W

Source Size: 3-mm arc

c. Ceiling Light Projector, ML-121.

(1) Description. The ML-121 Ceiling Light Projectors were manufactured by Carlisle and Finch Co., Cincinnati, OH, and Crouse-Hinds Co., Syracuse, NY, and represent the earlier type of cloud ceilometer still in use. The projector directed a fixed vertical beam (Figure 5). The NWS observer could then view the projected light spot on the cloud at night with a Clinometer from another fixed position and thereby determine the cloud height by triangulation. This procedure permitted the determination of cloud heights up to 10,000 ft (3050 m). The Ceiling Light Projector is now only used at a number of stations as a backup instrument. The fixed mount prevented a person of normal height from being able to look into the direct beam of the projector.

(2) Technical Specifications.

Source: 6-cm tungsten-halogen lamp

Beam Luminous Intensity: 2,000,000 cd

Beam Spread: 4° (70 mrad)

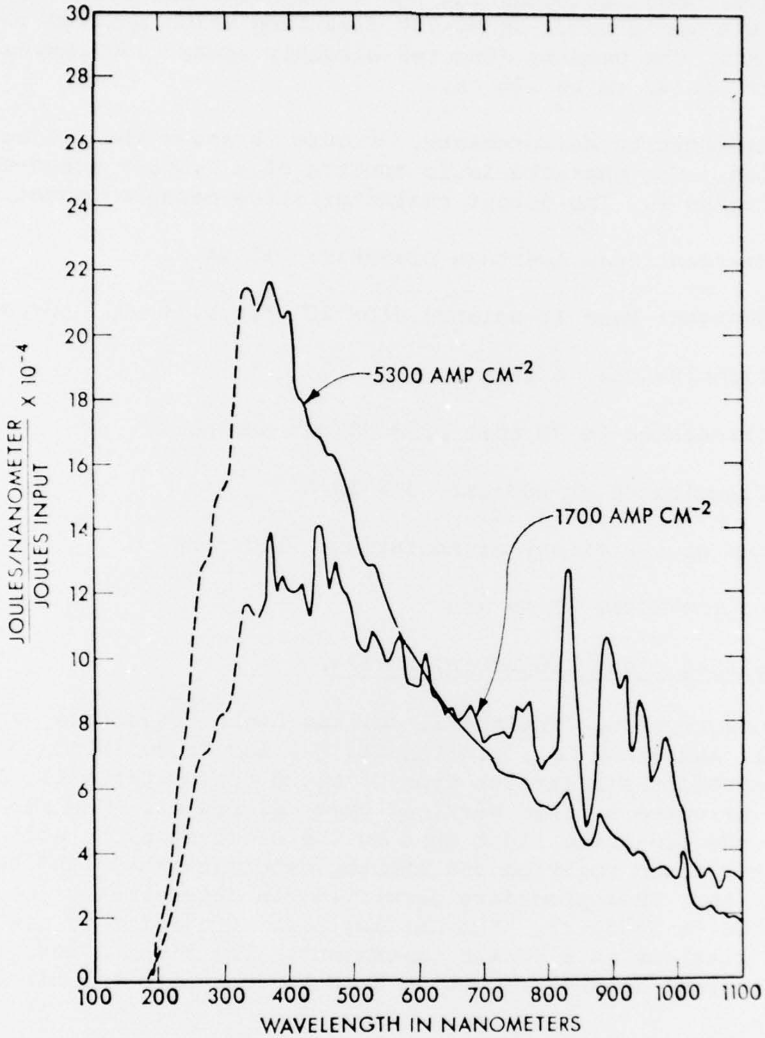


FIGURE 4. Spectrum of standard xenon flashlamps. The Impulsephysik Videograph uses a 2,000-V flashlamp which, like the upper curve (5300 Amp/cm^2), has a spectrum relatively rich in blue light.

FIGURE 5. Ceiling Light Projector, ML-121.

Lamp Type: GE 420G25P 420-W tungsten-halogen lamp with 3150° K color temperature

Projection Optics:
Primary Reflector Diameter: 42.5 cm
Primary Reflector Focal Length: 20.3 cm

(3) Radiometric Measurements.

Unit Measured: Serial Number 9-61

Accessible Irradiance (20° f.o.v.): 3.4 mW/cm^2 from 400 nm to 950 nm

Accessible Illuminance: 3,700 lx

d. Rotating Beam Ceilometer, Model K211.

(1) Description. The Rotating Beam Ceilometer is now the most commonly used ceilometer in the vicinity of airports in the United States. It is manufactured by Crouse-Hinds Co., Syracuse, NY. Figure 6a illustrates the device. Figure 6b shows the projected source (coiled-coil tungsten filament) as recorded by a camera at the beam port window using infrared film. The source is not visible to the normal eye because of the visible-blocking, infrared-pass filter cover. The beam scanned to permit triangulation of a broad range of cloud heights (Figure 7).

(2) Technical Specifications.

Projection Optics (two reflectors):
Relector Diameter: 61 cm
Reflector Focal Length: 25.4 cm

Lamps (two each): Type DS 300, 625 W

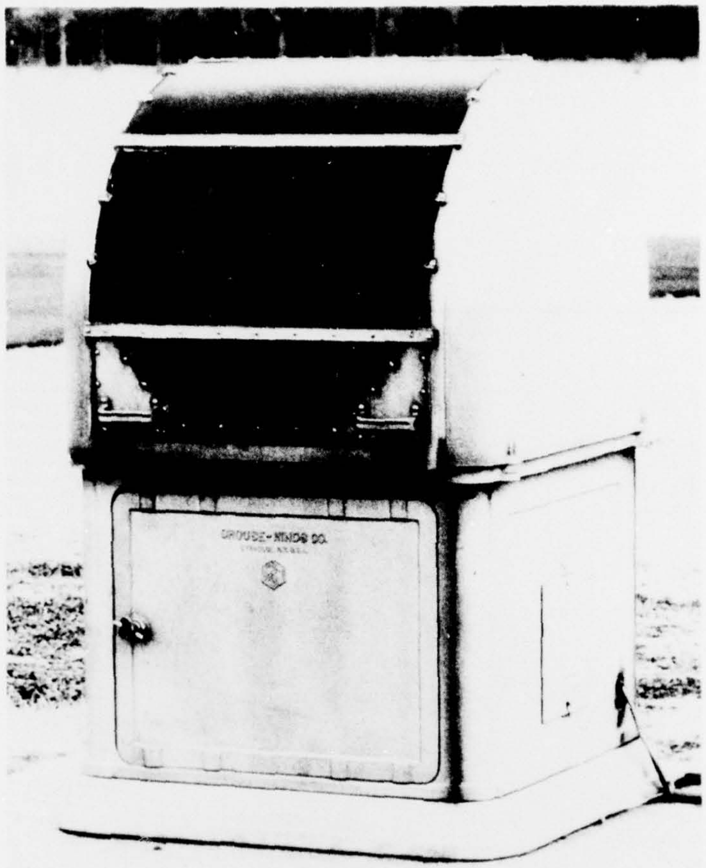
Light Modulation by Shutters: 120 Hz

Rotation Speed of Lamp Assembly: 5 rpm (i.e., the beam scan rate is 10 rpm, or one beam scan every 6 seconds)

(3) Radiometric Measurements.

Accessible Beam Radiant Exposure (static 7-mm aperture): 1.1 mJ/cm^2

Projected Source Size (near-field): 25 by 60 mrad



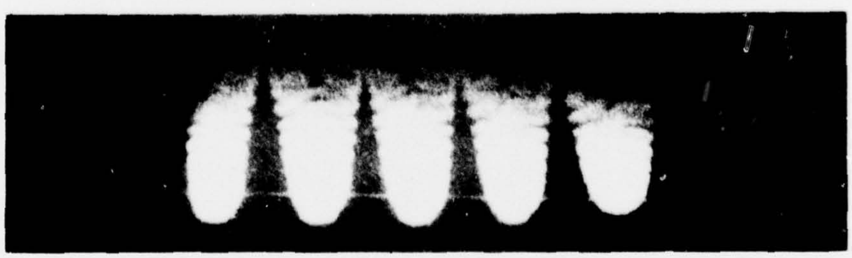


FIGURE 6. Rotating Beam Ceilometer (top) and infrared photograph of source taken at window (bottom).

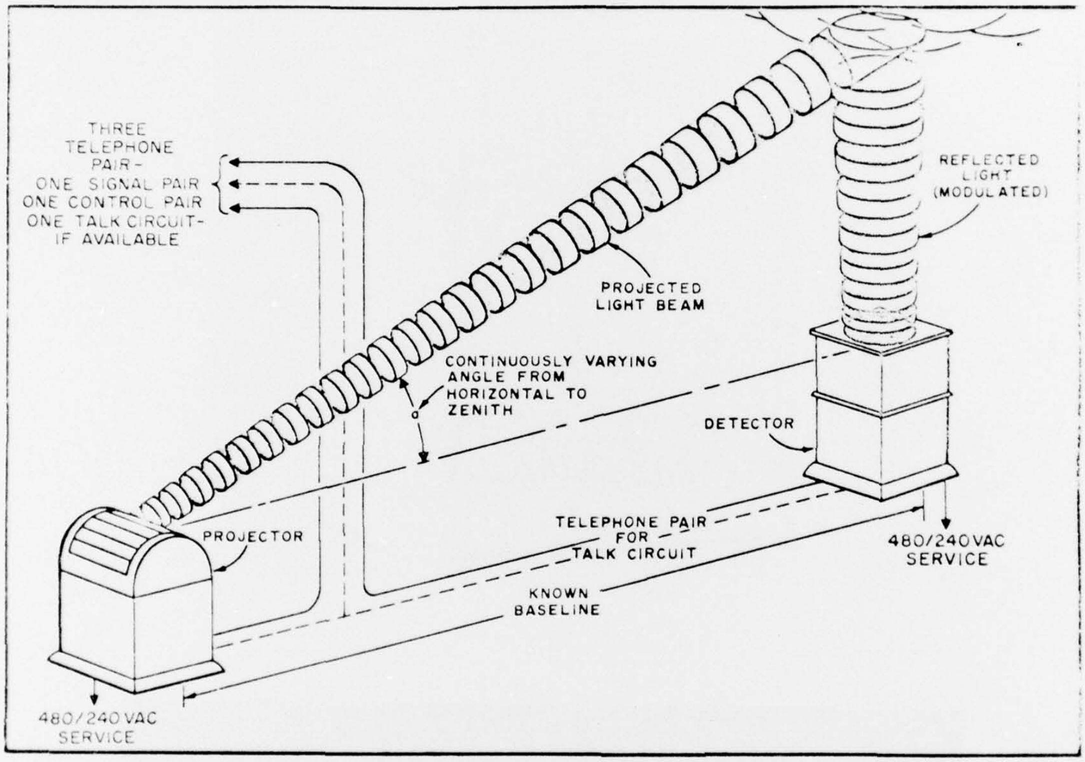


FIGURE 7. Schematic of the operation of the Rotating Beam Ceilometer.

Source Radiance: 20 W/($cm^2 \cdot sr$) (estimated) for 2900° K tungsten filament for the 750 nm - 1,400 nm region)

e. Laser Weather Identifier.

(1) Description. The Laser Weather Identifier is an experimental system which was undergoing development and evaluation at the Dulles Airport facility of NWS at the time of this study. It made use of two different lasers: a GTE Sylvania Model 941 CO_2 infrared continuous wave (cw) laser and a Spectra-Physics Model 120 He-Ne visible cw laser. The emergent beams were collimated and projected along two 25-m parallel, horizontal atmospheric paths approximately 175 cm above ground level (approximately at eye level for a 6-foot-tall person). In future use, the beam paths would be 100 m long and would presumably cross restricted areas of airfields but not across runways. The CO_2 beam was modulated at 10 Hz and directed from one shed to a detector in a second shed. The He-Ne laser was unmodulated and was directed along the same path as the CO_2 laser.

(2) Technical Specifications.

Specification	CO_2 Laser	He-Ne Laser
Output Power:	3.0 W	5-8 mW
Wavelength:	10.6 μm	632.8 nm
Collimator Objective Diameter	86 mm	50 mm
Initial Beam Diameter (1/e)	3.6 mm	0.6 mm
Initial Beam Divergence (1/e)	3.6 mrad	0.7 mrad
Final Beam Divergence (theory)	0.4 mrad	0.02 mrad
Hazard Classification of Final System	IV or IIIb	IIIa

(3) Radiometric Measurements.

(a) CO_2 Laser - not operable at time of study.

(b) He-He Laser:

Emergent Beam Power (total): 3.4 mW

Emergent Beam Power through a 7-mm aperture: 0.18 mW, (5%)

Emergent Beam Irradiance averaged over a 7-mm aperture: 0.47 mW/cm^2

Emergent Beam Diameter: 3.2 cm at 1/e-of-peak-irradiance points

6. DISCUSSION.

a. Sperry LIDAR Model LC5000/1 Ceilometer.

(1) Direct Viewing. The protection standard for a 5-kHz, 905-nm, 60-ns repetitively pulsed "point-source" Ga-As laser is 0.38 mW/cm^2 on an average-power basis (references 1-3, Appendix A). Therefore the beam is not hazardous to view directly (i.e., by intrabeam viewing). It is, however, hazardous to view through optical instruments having a magnifying power exceeding 2X.

(2) Hazard Classification. The Federal Laser Product Performance Standard (reference 5, Appendix A) prescribes a Class I emission limit of 0.098 mW average. TB MED 279 (reference 2, Appendix A) has a like limit for Class I. The ANSI No. Z136.1-1976 (reference 3, Appendix A) standard's Class I limit is slightly higher but is still less than one-fifth the total output of the Ceilometer through an 80-mm aperture. The device is therefore classified as a Class IIb system.

(3) Hazard Analysis. As the Ceilometer is presently used, there is no personnel hazard for a vertical path. An individual standing and peering over the exit tube would not be exposed to a hazardous level. Personnel in aircraft flying overhead would not be exposed to a hazardous level since the hazardous viewing condition with optical instruments applies only to fixed staring into the beam for several seconds.

b. Impulsephysik Videograph. The flashlamp's projected pulsed radiance was approximately 0.03 $J/(cm^2 \cdot sr)$ which is well below criteria which would be applicable to a visible laser source with a 50-μs pulse duration which is 0.39 $J/(cm^2 \cdot sr)$. The laser protection standard provides a conservative estimate of the actual hazard of such a flashlamp and is approximately the same criteria specified for an 18-mrad white-light source in reference 4, Appendix A.

c. Ceiling Light Projector. A tungsten-halogen lamp with a color temperature of 3150° K has a total radiance of approximately 70 $W/(cm^2 \cdot sr)$ and a radiance between 400 nm and 1,400 nm of 38 $W/(cm^2 \cdot sr)$. This radiance is not safe to view directly for 0.25 second for the source which subtends approximately 70 mrad at close range. The radiance standard for viewing such a source is $\sqrt{t}/\alpha t$ where t is the exposure duration up to 10 seconds and α is the angular subtense in radians, i.e., the radiance limit is 29 $W/(cm^2 \cdot sr)$ at 0.25s. Because of losses in the optical projection system, and an overestimate of source size, this analysis must be considered very conservative, but it does point out that direct intrabeam viewing of this source represents at least a marginally hazardous condition. Since the beam is not accessible to a person standing on the ground, and since the opportunity to look into the beam from aircraft at close range does not exist, there is no actual hazard except during maintenance.

d. Rotating-Beam Ceilometer. The protection standard recommended by reference 4, Appendix A, for continuous viewing of a near-infrared source with a 60-mrad angular subtense (α) is 10 W/(cm$^2\cdot$sr) which is a factor of two below the radiance of the Ceilometer source. The actual momentary exposure repeated continuously would represent an average radiance much less than the criteria. If the sources stopped rotating, continuous viewing of the tungsten source would not seem possible since there is no visual stimulus present to stare into.

e. Laser Weather Identification. Since the CO_2 laser was not operating at the time of this study, a complete hazard analysis is not possible. Because of losses in the infrared optics and modulator, it is reasonable to assume that the total output projected through an 80-mm aperture will not exceed 0.5 W, which is the limit of the Class III laser category. If this assumption is correct, then the hazard is limited to exposure to the direct beam through optical instruments. Indeed, for the CO_2 laser, the optical instrument would have to have specialized infrared transmitting elements. The emergent beam irradiances were: 0.47 mW/cm^2 (He-Ne) and 20 mW/cm^2 (CO_2, estimated). The protection standard for the He-Ne laser is 2.5 mW/cm^2 for 0.25-s momentary exposure and 1.0 mW/cm^2 for a 10-s exposure. The protection standard for the CO_2 laser is 100 mW/cm^2 for exposure periods exceeding 10 seconds.

7. CONCLUSIONS. Several optical radiation sources used in NWS weather instrumentation are potentially hazardous under unusual viewing conditions. Steps can be taken to warn persons potentially exposed to hazardous conditions at close ranges.

8. RECOMMENDATIONS.

a. Sperry LIDAR.

(1) Place a warning in the instruction manual for this instrument that personnel should not view the source from within the beam with magnifying optics exceeding 2X, if the beam is horizontal and therefore accessible.

(2) Place a cautionary warning label on future devices as specified in reference 5, Appendix A.

b. Impulsephysik Videograph. None.

c. Ceiling Light Projector. Place a warning in the maintenance manual to advise personnel not to stare into the lamp-source/projector-system during maintenance or testing.

d. Rotating Beam Ceilometer. Place a warning notice in the maintenance manual for this instrument to advise personnel not to view the source with or

without the "black-glass" infrared filter in place, if the lamps are not moving.

e. Laser Weather Identifier.

(1) Attempt to limit the final projected output of the CO_2 laser system to 0.5 W and 0.1 W/cm^2 and the output of the He-Ne laser system to 1-5 mW with an irradiance below 2.5 mW/cm^2.

(2) Use beam paths at 190 cm aboveground or higher if practicable.

David H. Sliney
DAVID H. SLINEY
Chief, Laser Branch
Laser Microwave Division

Wesley J. Marshall
WESLEY J. MARSHALL
Physicist
Laser Microwave Division

Pedro F. Del Valle
PEDRO F. DEL VALLE
1LT, MSC
Nuclear Medical Science Officer
Laser Microwave Division

APPROVED:

ROBERT T. WANGEMANN, Ph.D.
LTC, MSC
Chief, Laser Microwave Division

WILLIAM G. PEARSON
COL, MSC
Director, Radiation and Environmental Sciences

APPENDIX A

REFERENCES

1. AR 40-46, Control of Health Hazards from Lasers and Other High Intensity Optical Sources, 6 February 1974.

2. TB MED 279, Control of Hazards to Health from Laser Radiation, 30 May 1975.

3. American National Standards Institute (ANSI) No. Z136.1-1976, Safe Use of Lasers.

4. American Conference of Governmental Industrial Hygienists (ACGIH), "Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment with Intended Changes for 1976," Cincinnati, OH (1976).

5. Title 21, Code of Federal Regulation (CFR), 1976 ed., Part 1040, Performance Standard for Light-Emitting Products.

APPENDIX B

USEFUL CIE RADIOMETRIC AND PHOTOMETRIC TERMS AND UNITS[1,2]

RADIOMETRIC				PHOTOMETRIC			
Term	Symbol	Defining Equation	SI Unit and Abbreviation	Term	Symbol	Defining Equation	SI Units and Abbreviation
Radiant Energy	Q_e		Joule (J)	Quantity of Light	Q_v	$Q_v = \int \Phi_v dt$	lumen-second (lm·s) (talbot)
Radiant Energy Density	W_e	$W_e = \frac{dQ_e}{dV}$	Joule per cubic meter ($J \cdot m^{-3}$)	Luminous Energy Density	W_v	$W_v = \frac{dQ_v}{dV}$	talbot per square meter ($lm \cdot s \cdot m^{-3}$)
Radiant Power (Radiant Flux)	Φ_e, P	$\Phi_e = \frac{dQ_e}{dt}$	Watt (W)	Luminous Flux	Φ_v	$\Phi_v = 680 \int \frac{d\Phi_e}{d\lambda} V(\lambda)\, d\lambda$	lumen (lm)
Radiant Exitance	M_e	$M_e = \frac{d\Phi_e}{dA} = \int L_e \cdot \cos\theta \cdot d\Omega$	Watt per square meter ($W \cdot m^{-2}$)	Luminous Exitance	M_v	$M_v = \frac{d\Phi_v}{dA} = \int L_v \cdot \cos\theta \cdot d\Omega$	lumen per square meter $lm \cdot m^{-2}$
Irradiance or Radiant Flux Density (Dose Rate in Photobiology)	E_e	$E_e = \frac{d\Phi_e}{dA}$	Watt per square meter ($W \cdot m^{-2}$)	Illuminance (luminous flux density)	E_v	$E_v = \frac{d\Phi_v}{dA}$	lumen per square meter ($lm \cdot m^{-2}$) lux (lx)
Radiant Intensity	I_e	$I_e = \frac{d\Phi_e}{d\Omega}$	Watt per steradian ($W \cdot sr^{-1}$)	Luminous Intensity (candlepower)	I_v	$I_v = \frac{d\Phi_v}{dr}$	lumen per steradian (lm·sr) or candela (cd)
Radiance	L_e	$L_e = \frac{d^2\Phi_e}{d\Omega \cdot dA \cdot \cos\theta}$ [5]	Watt per steradian and per square meter ($W \cdot sr^{-1} \cdot m^{-2}$)	Luminance	L_v	$L_v = \frac{d^2\Phi_e}{dr \cdot dA \cdot \cos\theta}$ [5]	candela per square meter ($cd \cdot m^{-1}$)
Radiant Exposure (Dose, in Photobiology)	H_e	$H_e = \frac{dQ_e}{dA}$	Joule per square meter ($J \cdot m^{-2}$)	Light Exposure	H_v	$H_v = \frac{dQ_v}{dA} = \int E_v dt$	lux-second (lx·s)
				Luminous Efficacy (of radiation)	K	$K = \frac{\Phi_v}{\Phi_e}$	lumen per watt ($lm \cdot W^{-1}$)
				Luminous Efficiency (of a broad band radiation)	$V(\cdot)$	$V(\cdot) = \frac{K}{K_m} = \frac{K}{680}$	unitless
Radiant Efficiency[3] (of a source)	η_e	$\eta_e = \frac{P}{P_i}$	unitless	Luminous Efficacy[3] (of a source)	η_v	$\eta_v = \frac{\Phi_v}{P_i}$	lumen per watt ($lm \cdot W^{-1}$)
Optical Density[4]	D_e	$D_e = -\log_{10} \tau_e$	unitless	Optical Density[4]	D_v	$D_v = -\log_{10} \tau_v$	unitless
				Retinal Illuminance in Trolands	E_t	$E_t = \frac{L_v}{S_p}$	troland (td) = luminance in $cd \cdot m^{-2}$ times pupil area in mm^2

1. The units may be altered to refer to narrow spectral bands in which case the term is preceded by the word *spectral*, and the unit is then per wavelength interval and the symbol has a subscript λ. For example, spectral irradiance H_λ has units of $W \cdot m^{-2} \cdot m^{-1}$ or more often, $W \cdot cm^{-2} \cdot nm^{-1}$.
2. While the meter is the preferred unit of length, the centimeter is still the most commonly used unit of length for many of the above terms and the nm or um are most commonly used to express wavelength.
3. P_i is electrical input power in watts.
4. τ is the transmission
5. At the source $L = \frac{dI}{dA \cdot \cos\theta}$ and at a receptor $L = \frac{dE}{d\Omega}$